A Directional MAC Protocol for Ad Hoc Networks

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***Abstract*— Using directional antennas in wireless ad hoc networks can greatly improve the spatial reuse and the transmission range. However, it will cause the deafness problem, which greatly impairs the network performance. This paper proposes a new MAC protocol SDMAC (Selectively Directional MAC) that can effectively address the deafness problem and significantly improve the network throughput. Simulation results show that our protocol can achieve a better performance than the existing MAC protocols using directional antennas.**

I. Introduction

A wireless ad hoc network is a network where nodes can communicate with each other without the support of infrastructure. It can be set up easily and quickly with low cost. As a result, wireless ad hoc networks have many applications for commercial and military purposes.

Since the wireless channel is shared by all the nodes in the network, a medium access control protocol (MAC) is needed to reduce the collision. The IEEE 802.11 DCF (Distributed Coordination Function) is such a protocol, known as Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) with an optional use of RTS/CTS [1]. This protocol has been widely used in wireless ad hoc networks and our study here is also based on this protocol architecture.

IEEE 802.11 assumes omnidirectional antennas for the nodes in the network. So during a transmission, all nodes in the neighborhood of a sender or a receiver are expected to keep silent to avoid collision or interference with the ongoing transmission. This leads to low spatial reuse. On the other hand, when directional antennas are used, we can allow several transmissions at the same time without interfering with each other. Thus, the spatial reuse can be highly improved. The transmission range can also be increased because of the larger antenna gain and less interference.

However, when we use directional antennas, deafness is a severe problem [2]. This happens when a node sends out a RTS to the intended receiver but gets no response. Then the sender will double its contention window and then backoff. If the intended receiver is engaged in a long data transmission, the sender will fail to get CTS for several times. After the receiver finishes its transmission and becomes idle, the sender will have a large contention window and may probably have chosen a very long backoff period. So the channel will be idle for a long time. The worse case happens when the sender drops the packet because it has exceeded the maximum number of unsuccessful attempts.

This paper proposes a new protocol to address the deafness problem. In this protocol, two types of directional RTS/CTS (DRTS/DCTS) are used: Type I DRTS/DCTS is used to initiate the transmission and Type II DRTS/DCTS is used to notify the neighbors of the forthcoming data transmission. Every node in the network keeps two tables: one table contains the deaf nodes and their corresponding periods for being deaf, called deafness table; the other table contains several directional NAVs (DNAV), one for each direction, called DNAV table. By exchanging Type I DRTS/DCTS which contains their own information on DNAVs (N bits for N directions: bit n is 0 if DNAV[n] has expired and is 1 otherwise), the sender and the receiver can negotiate on a short time to send out Type II DRTS/DCTS to notify their neighbors of the impending transmission. A distributed algorithm is run to reduce the overhead caused by the transmission of Type II DRTS/DCTS. The nodes that receive Type I DRTS/DCTS will set the DNAV for the direction in which the packets are received. The nodes that receive Type II DRTS/DCTS will set the DNAV for the direction of data transmission, which is indicated by the 'Outgoing Beam' field (one new field added in the frame) in Type II DRTS/DCTS. Besides, they will also put both the sender and the receiver of Type II DRTS/DCTS into the deafness table. A node can send out a packet only if the DNAV of the outgoing direction of the packet is not set, as well as the intended receiver is is not in the deafness table.

The rest of this paper is organized as follows. We present the related work in the next section. In section III we briefly introduce IEEE 802.11 and our directional antenna model. In section IV we describe the deafness problem. Section V details our proposed protocol SDMAC. The simulation results are shown in section VI. We finally conclude this paper in section VII.

II. Related work

Many MAC protocols for wireless ad hoc hoc networks using directional antennas have been proposed in the past. Vaidya et al. propose DMAC in [5]. They use directional RTS (scheme 1) or omnidirectional RTS if all antennas sense an idle channel (scheme 2). The CTS frames are always sent omnidirectionally. It is assumed in the protocol that each node knows exact locations of the other nodes and each node transmits signals based on the known physical positions of the

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intended receiver. Nasipuri et al. propose in [9] a MAC protocol using omnidirectional RTS/CTS proceeding the directional DATA transmission. They do not need the physical location of the nodes. Ramanathan [10] analyzes the performance of aggressive and conservative collision avoidance model, with power control and neighbor discovery. There are also some protocols like [12] using directional virtual carrier sensing combined with a DNAV table to increase the spatial reuse of the network. Choudhury et al. propose a MAC protocol [3] using multi-hop RTSs to establish links between nodes far away from each other, and then transmit CTS, DATA, and ACK over a single hop. In these papers, the main objective is to improve the network throughput by increasing spatial reuse of the network. They do not take deafness problem into consideration, while it is indeed a severe problem in most of these protocols.

In order to address the deafness problem, Korakis et al. propose Circular DMAC in [6]. But it has a great constant overhead due to the circular transmission of RTS and the neighboring nodes of the receiver still suffer from deafness problem. Besides, the CTS may not be received after the circular transmission of RTS, while the neighboring nodes still keep silent. This results in a low channel efficiency. Choudhury and Vaidya also study the deafness problem in [2] and propose a tone-based solution. They split the channel into two sub-channels. One channel is used to transmit RTS/CTS/DATA/ACK and the other one is used to transmit the tones. In this way, they can achieve a better performance at the cost of an increased complexity of the protocol. In [7], Li et al. propose DMAC-DA to address the deafness problem. It also has a great constant overhead and there could be many interferences to the ongoing transmission.

While most of the previous protocols just consider the beamforming at the transmitter side, our proposed protocol SDMAC fully utilizes the advantages of directional antennas at both the transmitter and the receiver side. SDMAC implements a distributed algorithm, such that the sender and the receiver can negotiate on spending a short time to transmit Type II DRTS and DCTS simultaneously. This algorithm can ensure that our protocol has a smaller overhead than the protocols in [6] [7]. In SDMAC, the sender and the receiver of received Type II DRTS/DCTS are put into the deafness table. Thus the deafness problem can be greatly alleviated. SDMAC also uses a different method to set the directional NAV (DNAV), which can greatly reduce the interference to the ongoing transmission.

III. Preliminaries

A. IEEE 802.11

The fundamental access method of the IEEE 802.11 MAC is a DCF (Distributed Coordination Function) known as Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) with an option of RTS/CTS. The four-way handshake procedure (RTS/CTS/DATA/ACK), which is used to deal with the hidden terminal problem, is as follows: Before a node begins to transmit, it should first sense the channel to determine

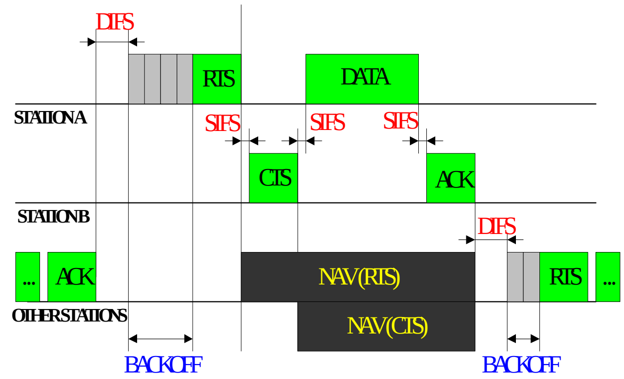


Fig. 1. Timeline of IEEE 802.11

whether there is any ongoing transmission. If the channel is busy, the node shall defer until the channel is sensed idle for a period of DIFS. Then the node randomly chooses a backoff period according to the contention window and starts a backoff timer and backoff. The backoff timer decreases by 1 after the channel is idle for the duration of a particular backoff slot. If the channel is sensed busy during any slot in the backoff interval, the backoff timer will be suspended. It can be resumed only after the channel is idle for a period of DIFS again. After the backoff timer reduces to 0, the sender sends out a RTS omnidirectionally. After correctly receiving the RTS, the receiver responses with a CTS a period of SIFS later. Similarly, after correctly receiving the CTS, the sender begins to transmit the data a period of SIFS later. This transmission ends after the receiver correctly receives the data and responses with an ACK. This process is also shown in Fig. 1. All four kinds of frames contain an estimated duration of the rest time of the transmission. Other nodes that receive these frames update their NAVs (Network Allocation Vector) with the duration. Every NAV decreases by 1 after a time slot. Those nodes are only allowed to transmit after it senses the channel idle for a period of DIFS after their NAVs expire.

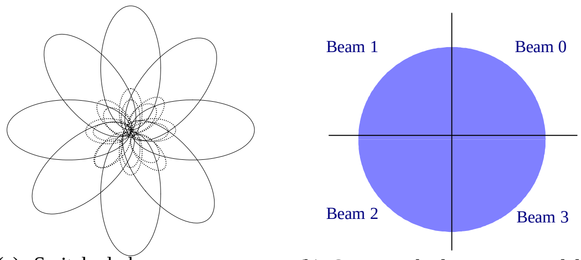
B. Directional Antenna Model

The gain of an antenna in direction $\vec{d} = (\theta, \phi)$ is given in [8] by:

$$G\left(\vec{d}\right) = \eta \cdot \frac{U\left(\vec{d}\right)}{U_{ave}} \tag{1}$$

where $U\left(\vec{d}\right)$ is the power density in the direction $\vec{d}$, U_{ave} is the average power density over all directions, η is the efficiency of the antenna which accounts for losses. Clearly, we can see that an omnidirecitonal antenna has a gain of 0dB and a directional antenna has a higher gain than that. Due to the higher gain and less interference when it's beamforming in a specific direction, a directional antenna can give us a longer transmission distance than omnidirectional antennas.

There are three primary types of directional antenna systems — switched beam antenna system, steered beam antenna system, and adaptive antenna system [4]. In this study, we



(a) Switched beam antenna system. (b) Our switched antenna model.

Fig. 2. Switched beam antenna model

use the switched beam antenna system, which consists of several highly directive, fixed, pre-defined beams and each transmission uses only one of the beams. One such antenna with eight beam directions is shown in Fig. 2(a). This system detects the received signal strength and chooses from one of the beams that gives the highest received power or SINR (Signal-to-Interference and Noise Ratio). Thus, we can easily get the beam direction in which we receive the signal. This is very useful in our scheme.

Our study assumes that there are N beams exclusively and collectively covering all directions in a switched beam antenna system. We also assume that when a directional antenna is engaged in transmission in one direction, the signal arriving in other directions will cause little interference to the ongoing transmission, i.e., we assume there is no side lobe antenna gain. Such an antenna model with four beams is shown in Fig. 2(b).

IV. Deafness problem

Directional antennas can provide us with a much higher spatial reuse. We can allow several transmissions carried out at the same time, which is impossible when we use omnidirectional antennas. In the scenario 1 shown in Fig. 3, by using directional antennas we can allow the transmission between A and B, and the transmission between C and D at the same time.

However, when we use directional antennas, deafness is a severe problem [2] [3]. This happens when a node sends out a RTS to the intended receiver but gets no response. Then the sender will double its contention window and then backoff. If the intended receiver is transmitting or receiving a long data, the sender will fail to get CTS for several times. So after the receiver finishes its transmission and becomes idle, the sender will have a large contention window and may probably have chosen a very long backoff period. Then the channel will be idle for a long time. What is worse, the receiver may want to initialize a new transmission with other nodes. It will choose a backoff interval according to a much smaller contention window than that of the sender. As a result, the receiver will likely be able to start another transmission before the sender sends out its RTS. Thus, the sender will keep deaf for a very long time. It may even drop the packet after it exceeds the maximum number of unsuccessful attempts. Scenario 2 in Fig. 3 shows a scenario for the deafness problem. In this case, there

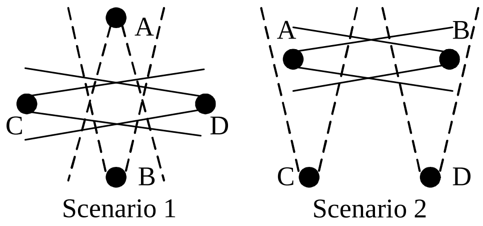


Fig. 3. Two scenarios when directional antennas are used.

is a transmission between node A and node B. During this transmission, A will not be able to receive the RTS from C because it is beamforming in a different direction. So C will not get any response from A. Similar to that, D will get no response from B if it sends a RTS to B. Thus, both C and D suffer from the deafness problem.

V. Proposed protocol

A. Protocol Description

This section details the proposed protocol: Selectively Directional MAC (SDMAC). In this protocol, every node keeps two tables. One table, called deafness table, contains the deaf nodes and their corresponding periods for being deaf. The other table, called DNAV table, contains several directional NAVs (DNAV), one for each direction. All nodes engaged in transmission send and receive unicast packets directionally and listen to the channel omnidirectionally when they are not doing transmission. We assume every node knows in which direction to transmit packets to the other nodes so that it can send DRTS to the intended receiver directly. This kind of information can be achieved through the GPS system or by some neighbor discovery process [10] [11]. SDMAC works as follows.

Type I DRTS/DCTS Exchange: The sender first sends Type I DRTS directly to the receiver in the specific direction. Type I DRTS frame has two more fields than the RTS frame in IEEE 802.11. One field called “Outgoing Beam” contains the outgoing beam number which is one byte long. It indicates the beam direction that the sender uses to transmit Type I DRTS to the receiver. The other field called “Beam Status” describes the status of all the beams. One bit for each beam, 0 stands for an expired DNAV and 1 otherwise. In this scheme, this field takes one byte, which can be adjusted according to the number of beams each node has. The duration field of Type I DRTS is set according to Eq. 2.

$$Duration_{rts1} = 3 * SIFS + T_{cts1} + T_{data} + T_{ack} \quad (2)$$

where T_{cts1}, T_{data}, T_{ack} represent the transmission times of Type I DCTS, DATA, and ACK respectively.

The receiver then responses with Type I DCTS in the direction in which it receives Type I DRTS. The Type I DCTS frame has the same format as the Type I DRTS frame. The outgoing number field of Type I DCTS indicates the beam the receiver uses to transmit Type I DCTS to the sender. The duration field of Type I DCTS is set according to Eq. 3.

$$\begin{aligned} Duration_{cts1} = {} & Duration_{rts1} - T_{cts1} \\ & + M * SIFS + M * T_{cts2} \end{aligned} \quad (3)$$

TABLE I

TYPE I DRTS/DCTS FRAME FORMAT

Frame Control	Duration	Receiver Address	Transmitter Address	Outgoing Beam	Beam Status	Frame Check

TABLE II

TYPE II DRTS/DCTS FRAME FORMAT

Frame Control	Duration	Receiver Address	Transmitter Address	Outgoing Beam	Frame Check

where M is determined by the distributed scheduling algorithm. It means that the receiver finds out that a period of $M * (T_{cts2} + SIFS)$ will be need to send out Type II DRTS/DCTS. The detailed of this algorithm will be shown later.

The Type I DRTS/DCTS frame is shown in Table I.

Type II DRTS/DCTS Notification: After the Type I DRTS/DCTS exchange process, both the sender and the receiver will know each other's beam status. Based on this information, the sender and the receiver make their own decision on the schedule of sending Type II DRTS and DCTS respectively and simultaneously without collision. Here, no collision means that the other nodes will not receive DRTS and DCTS at the same time so that each time they will receive only one of these two frames. Then, according to the schedule, the sender and the receiver send out Type II DRTS and DCTS, respectively, counterclockwise in directions where the DNAV has expired. Our protocol can make the sender and receiver spend a short time on this notification process. The details of this scheduling algorithm will be discussed later. Type II DRTS and DCTS frames have the same format, thus they will have the same transmission time. The frame format is shown in Table II. If the scheduling algorithm gets a result that the sender and the receiver need to spend a period of $M * (T_{rts2} + SIFS)$ on sending out Type II DRTS/DCTS, the duration field of the kth DRTS/DCTS frame is set as shown in Eq. 4 and Eq. 5.

$$\begin{aligned} Duration_{rts2} &= (M-k+1)*SIFS \\ &\quad +(M-k-1)*T_{rts2} \\ &\quad +T_{data}+T_{ack} \end{aligned} \quad (4)$$

$$\begin{aligned} Duration_{cts2} &= (M-k-2)*SIFS \\ &\quad +(M-k-1)*T_{cts2} \\ &\quad +Duration_{rts1}-T_{cts1} \end{aligned} \quad (5)$$

where $0 \leq M \leq N$, $0 \leq k \leq (M-1)$, and N is the number of beams. T_{rts2} and T_{cts2} represent the transmission time of Type II DRTS/DCTS respectively.

DDATA/DACK Transmission: The scheduling algorithm mentioned above can also ensure that the sender and the receiver can beamform toward each other at the same time to prepare for the data transmission. The transmission ends when the sender receives directional ACK from the receiver. The duration field of DATA frame is set as shown in Eq. 6.

$$Duration_{data} = T_{ack} + SIFS \quad (6)$$

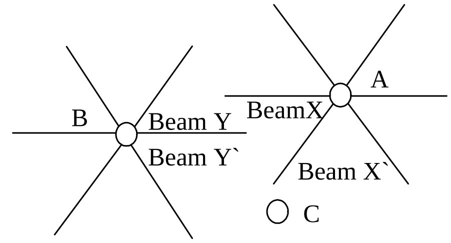


Fig. 4. An example for scheduling on sending out Type II DRTS/DCTS simultaneously without collision

B. Key Techniques

In this subsection we detail some key techniques used in the proposed protocol SDMAC.

Differentiation of two kinds of DRTS/DCTS: As mentioned before, in this protocol, there are two types of DRTS/DCTS. Type I DRTS/DCTS is exchanged between sender and receiver to initiate the transmission. Type II DRTS/DCTS is used by the sender or the receiver to inform their neighboring nodes of the forthcoming data transmission. For Type I and Type II DRTS/DCTS, we set the "Receiver Address" field to the MAC address of the receiver of the frame and set the "Transmitter Address" to that of the sender of the frame. Differentiating two kinds of DRTS/DCTS can help set DNAV for the nodes, which will be discussed later.

Transmitting Type II DRTS/DCTS simultaneously: Assume node A and B use beam X and beam Y, respectively, to exchange the Type I DRTS/DCTS. After that, A and B use beam X' and Y', respectively, to send Type II DRTS/DCTS to notify their neighbors of the forthcoming transmission. We say beam X' of node A and beam Y' of node B collide if A's transmission of Type II DRTS using beam X' and B's transmission of Type II DCTS using beam Y' collide at some neighbor nodes.

Consider the case shown in Fig. 4, where A is the sender and B is the receiver. If A transmits Type II DRTS on beam X' and B transmits Type II DCTS on beam Y' at the same time, node C will receive both packets because it is listening to the channel omnidirectionally. In this situation, node C cannot receive any packet successfully and we say beam X' of node A and beam Y' of node B collide. Since node C does not know the impending transmission between node A and node B, it will be able to send packets to these two nodes, and then the deafness problem arises. As a result, this kind of collision should be avoided to ensure that the neighboring nodes can receive Type II DRTS or DCTS successfully.

Observation: If node A and B use beam X and beam Y, respectively, to exchange the Type I DRTS/DCTS, then node A can conclude that beam Y' of node B and beam X' of node A collide if $(Y' - X')(Y' - Y) \leq 0$. Similarly, node B can conclude that beam X' of node A and beam Y' of node B are collide if $(X' - Y')(X' - X) \leq 0$. This can be seen clearly from Fig. 4.

A Distributed Algorithm: In Type II DRTS/DCTS notification process, the sender and the receiver check the beams counterclockwise beginning from the beam next to the former

TABLE III

DEAFNESS TABLE

Node	NAV

TABLE IV

DNAV TABLE

DNAV[1]	DNAV[2]	DNAV[3]	...	DNAV[N]

one used to exchange Type I DRTS/DCTS. In the example above, if every node has N beam directions, A will start from beam $(X+1) \mod N$, and B will start from beam $(Y+1) \mod N$. We call a beam idle if it has an expired DNAV and busy otherwise. The algorithm works as follows: (1) When both sender and receiver have idle beam directions, e.g., X' and Y', they transmit simultaneously if beam X' and beam Y' do not collide. Otherwise, the one that has searched fewer beams sends first while the other waits on that beam. For example, in Fig. 4, node A transmits using beam X' and node B waits on beam Y'. We should notice that there is no possibility that two nodes have searched the same number of beams when the two beams they are checking collide. (2) When one node finds an idle beam while the other one is checking the last beam and finds it busy, then the first node transmits and the second node waits on that beam. (3) When both nodes have finished searching the other N - 1 directions, this process terminates and the DDATA/DACK Transmission process follows.

This is a distributed algorithm such that the sender and the receiver can make their own decision on the schedule of sending DRTS and DCTS simultaneously without collision. In the protocol proposed in [7] [10], the sender spends time transmitting DRTS in directions with expired DNAV and waiting for the same time in directions with non-expired DNAV. Our scheme can make the sender and receiver agree on a much less time for sending Type II DRTS/DCTS, and hence has much less overhead. Besides, in the protocol [10], only sender sends out DRTS. While in our protocol, both the sender and the receiver send out DRTS/DCTS to inform the neighbors, which can better address the deafness problem.

A new way of setting DNAV: Every node keeps two tables: Table III and Table IV. When a node receives Type I DRTS/DCTS or a DATA packet, it sets DNAV in the direction in which it receive the packet. When a node receives Type II DRTS/DCTS, it adds the sender and intended receiver, and their corresponding deaf periods into Table III. It also sets the DNAV in the direction indicated by the 'Outgoing Beam' field of the frame. This is because we should block the transmission in the same direction as that of the DATA or ACK transmission to avoid the possible collision at the receiver or the sender. When a node wants to send packets using beam M, it first checks whether DNAV[M] in Table IV has expired. If so, it then checks Table III to see whether the intended destination node is in the table. If so, it will not transmit. Otherwise, the node can transmit using beam M.

Tuning the power: In this protocol, we use an enhanced antenna gain for directional transmissions in order to have a larger directional transmission range. In this way, the average number of end-to-end hops can be reduced and the end-to-end throughput can be increased.

The routing protocols such as AODV (Ad-hoc On-demand Distance Vector Routing) and DSR (Dynamic Source Routing) find a path between two nodes by broadcasting Route Request Packets (RREQ). Since we use a larger antenna gain for directional transmission and a smaller antenna gain for omnidirectional transmission, the transmission range of broadcasting packets will be smaller than that of data packets. Then the paths found by these routing protocols may not be the shortest paths. As a result, in the protocol we increase the transmitting power for omnidirectional transmissions so that they have the same transmission range as that of directional transmissions.

VI. PERFORMANCE ANALYSIS AND EVALUATION

A. One-hop Scenarios

We first look at some simple scenarios shown in Fig. 5. It can clearly show that our proposed protocol can outperform many former proposed protocols.

In scenario 1, node B is in transmission range of node A. Node C is in the transmission of B but not in the transmission range of A. It is in the sensing range of node A. There are two flows: node A to node B (Flow 1) and node B to node C (Flow 2). We choose this scenario to compare SDMAC with DMAC. When DMAC is used, RTS is sent out directionally and CTS is sent out omnidirectionally. So A cannot receive either of the RTS and CTS when B is transmitting to C and it suffers from the deafness problem. However, when SDMAC is used, A will receive the Type II DRTS sent by B, so it will not transmit to B when it is deaf to A.

In Scenario 2, node B is in transmission range of both node A and node C. Node C is in the transmission range of B and the sensing range of A. It is in the sensing range of node A. The distance between B and C is much larger than that between B and A. There are two flows: node A to node B (Flow 1) and node C to node B (Flow 2). We choose this scenario to compare SDMAC with Ciruclar-DMAC (CDMAC) [6]. When using CDMAC, A and C cannot receive the DRTS sent by each other, so they both try to send packets to B. Since the CTS is sent out directionally, C will not be able to receive the CTS from B to A when they are doing transmission and so it suffers from the deafness problem. What is more, since the distance between B and C is much larger than that between B and A, then the signal from C will be probably ignored if the signal power is less than that of the signal from A by a threshold. Thus flow 2 will be dominated by flow 1 at high date rates. In SDMAC, B will send out Type II DCTS circularly to solve this problem.

In Scenario 3, flow 1 (node A to node B) and flow 2 (node C to node D) interfere with each other. We choose this scenario to compare SDMAC with DMAC-DA [7]. DMAC-DA allow these two flows going at the same time, which will definitely degrade the network performance. On the contrary,

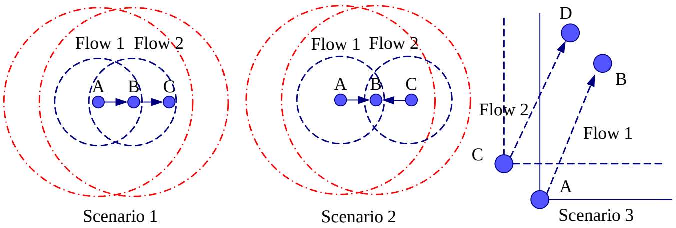


Fig. 5. Scenario 1 is for the comparison between SDMAC and DMAC; Scenario 2 is for the comparison between SDMAC and Circular-DMAC. In this two scenarios, Small circle stands for transmission range and big circle stands for the sensing range. Scenario 3 is for the comparison between SDMAC and DMAC-DA.

TABLE V

SOME SIMULATION PARAMETERS.

Parameters	Value
Channel frequency	2.4 GHz
Data rate	2Mbps
Packet size	512 bytes
RTS retry limit	7
Directional antenna gain	12.0 dBi
RX threshold	-81.0 dBi
CS threshold	-91.0 dBi
Beam directions	8

SDMAC blocks the transmissions in parallel directions. So we can achieve a better performance. Besides, due to a distributed algorithm, SDMAC has a lower overhead than DMAC-DA.

B. A Multi-hop Scenario

We evaluate the performance of our MAC protocol in multi-hop networks. We compare our protocol with IEEE 802.11 [1], DMAC [5], Circular-DMAC [6], and DMAC-DA [7]. We use a 1000m x 1000m 2D topology in which there are 50 nodes. Ten nodes are chosen to be CBR (Constant Bit Rate) sources and their destination nodes are randomly chosen. The network uses AODV (Ad Hoc OnDemand Distance Vector Routing) routing protocol. Some simulation parameters are shown in Table V. Fig. 6 shows the simulation results on the aggregated throughput. We can see that SDMAC can achieve higher throughput than all the other MAC protocols. This indicates that our protocol can greatly alleviate the deafness problem and achieve a better performance.

VII. CONCLUSION

This paper proposes a new MAC protocol SDMAC for wireless ad hoc networks using directional antennas. The simulation results show that the proposed protocol can greatly alleviate the deafness problem and improve the network throughput.

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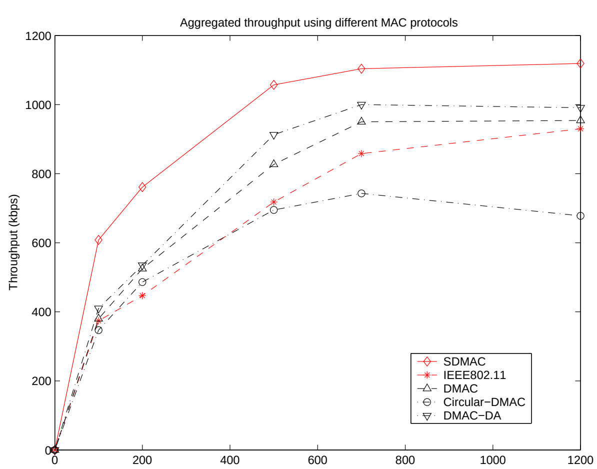

Fig. 6. Compare different MAC protocols in terms of aggregated throughput.